A METHOD FOR DETERMINING THE WALL THICKNESS AND THE SPEED OF SOUND IN A TUBE FROM REFLECTED AND TRANSMITTED ULTRASOUND PULSES

This application is a continuation in part of U.S. Patent Application Number 10/055,461, filed January 23, 2002, now allowed, which claims the benefit of U.S. Provisional Application No. 60/263,650 filed January 23, 2001.

BACKGROUND OF THE INVENTION

The present invention generally relates to the use of ultrasonic pulses, or waves, to measure the properties of objects in the wave's path, and more particularly to the use of an ultrasonic wave source to determine both the thickness of pipes and tubes and the speed of sound within the same, both from the same set of recorded data and without recourse to assumed or predetermined values of properties unique to the pipe or tube being measured.

Various types of non-destructive measurement methods have been employed in the art for determining an object's structural properties. One method, utilizing ultrasonic waves, is particularly appealing due to its accuracy, relative low cost, and safety. It is commonly used to determine object thickness, as well as to detect flaws and discontinuities. Accordingly, its use in inspecting objects with hollow internal cavities not readily amenable to visual perception or the placement of a conventional measuring device is especially valuable. Exploitation of the wavelike nature of acoustic signals, when combined with knowledge of the constitutive properties of the material making up the object, leads to reasonably accurate measurement of the object. Ultrasonic testing is well-suited to the measurement of material thickness, including layered or nonhomogenous materials with acoustically disparate properties. By taking advantage of different reflective properties of the constituent materials and the speed of propagation of the sound wave therethrough, the thickness of the material can be readily calculated.

The operation of a conventional ultrasonic measurement system in the time domain is relatively straightforward. Typically, a pulse generator produces an electrical signal with

certain characteristics. This signal is sent to one or more transducers, where the signal is converted to an ultrasonic wave, which is then transmitted in the direction of a target object to be measured. Typically, both the target object as well as the transducers are in an acoustically-coupled medium, such as water, to enhance the transmission of the waves relative to a more rarified medium, such as air. Echoes reflected from the object return to the transducers, which convert the echo into a corresponding electrical signal, which is then routed to a receiver, where the signals can be counted or digitized, analyzed and stored. Analysis of the echo shows that the thickness of the object can be equated to a product of the speed of sound and the propagation time of the ultrasound wave within the object. Once any two of these three values are known, the third can be easily calculated. Nevertheless, the accuracy of some calculations based on time of flight data is subject to limitations. For example, in the conventional analysis discussed above, the speed of sound in the object being measured is assumed. Furthermore, even if the assumed speed was accurate for one temperature, it might not be for another. In addition, in the conventional analysis, the frequency-dependence of the speed of sound is not considered; the spectral content can become significant if the object being measured exhibits dispersive behavior, for example, where the speed of sound is frequency-dependent. These assumptions and simplifications, based on a constant, predetermined value, may introduce errors into subsequent thickness calculations. Moreover, for objects with multiple walls (such as a tube), there are limitations on placement of the ultrasonic transducers, especially where the inside diameter of the tube is small. Existing methods, while appropriate for geometrically simple structures, such as flat plates, are incapable of measuring individual wall thickness of multi-walled objects.

Current methods to measure the wall thickness of tubes and tubular-shaped objects either depend on an assumed sound velocity in the tube, or use a calibration procedure. Both of these approaches have disadvantages. In the former case, inaccuracies can result, either from improper characterization of the constitutive properties of the material in the object, or from inhomogeneities in the material itself, such as due to the presence of cladding, alloying or composite structures. Insofar as the equations used to calculate thickness depend on the speed of sound in the object being measured, any inaccuracies in

that assumed quantity will produce errors in thickness calculations. In the latter case, calibration can be complicated and unreliable. In addition, it often must be conducted off-line, thereby taking away from precious measurement time.

It is well-known in the art to compensate measurements for variations in the temperature of the acoustic couplant medium (typically water). However, the temperature of the water can be significantly different than the temperature of the object in the water, especially when the object is passing through the water as part of a manufacturing step, such as the extrusion of tubes and related objects. Thus, assigning a temperature value (such as the measured temperature of the water in which the object is placed) to an object being measured may not accurately reflect the true temperature within the object.

The time-domain method provides a single scalar value of the speed of sound. If the sound wave passes through a dispersive medium, its determination will depend on the frequency characteristics of the transducers used in the measurement. However, an inherent part of the time-domain method is that such frequency-dependent values are not made manifest. Thus, in certain circumstances, additional measurement accuracy can be realized by using frequency-domain analysis, which can determine the phase velocity and group velocity at different frequencies. In the present context, the term "speed", although in the strictest sense a scalar quantity, is used generally to represent both scalar and vector quantities in either time-domain or frequency-domain analyses. Contrarily, the more specific terms "phase velocity" and "group velocity" are both functions of frequency, and their use is restricted to frequency-domain analyses. The frequency-dependent quantities, while usually not as big of a contributor to a thorough and accurate determination of object thickness as the speed of sound in the object, can nonetheless provide additional insight into secondary levels of measurement error, especially when conducted on highly dispersive materials.

Accordingly, what is needed is a method for measuring object thickness and sound velocity through the object simultaneously, such that neither assumed properties nor the use

of complicated calibration procedures is required. What is further needed is a method that maintains high accuracy in measuring the thickness of a highly dispersive object.

BRIEF SUMMARY OF THE INVENTION

These needs are met by the present invention, where a new method for determining the sound propagation velocity and wall thickness of a tubular workpiece is described. As used in the present context, a tubular workpiece need not be cylindrical in cross-section; it could be elliptical or even rectangular. It will be appreciated by those skilled in the art that the present method could also be used on elongate, non-tubular members, such as cylindrical or elliptical solid rods and related structure. Extraction of the sound velocity and tube thickness from the sensed data obviates the need for using a contact-based method for measuring the tube thickness, which can be either inconvenient or inaccurate under certain conditions. It also avoids calculation errors by utilizing actual measured speed of sound in the tubular workpiece, rather than assuming a fixed, predetermined value. It also extends the use of multiple transducers to objects with complex geometries, such as tubes, where access limitations prohibit transducer configurations for single wall measurements to be used. The method is particular useful for real-time measurement of multiple wall thickness when the sound speed of the specimen may change, such as due to a change of temperature. Unlike the prior art, where the speed of sound in the object is assumed and the measured data is corrected post facto to account for temperature variations within an acoustic couplant medium (or some other location in close proximity to the object), the data taken by the method of the present invention inherently includes temperature-related effects, as the speed of sound through the medium is a necessary concomitant of the time of flight measurements. Accordingly, temperature-related errors are minimized or abrogated entirely. In circumstances where acoustic dispersion within the tube material may be significant, this new method can provide further enhanced accuracy by taking into account the spectral content of the propagated wave through the tube walls.

According to an aspect of the present invention, a method of determining the wall thickness of a tubular workpiece and the speed of sound within the workpiece from a single set of recorded data is disclosed. The method comprises the steps of configuring an

acoustic couplant medium and defining a transmission path therein, and selectively disposing the tubular workpiece in the medium such that the workpiece is in the transmission path and that each interface between a surface of the workpiece and the medium along the transmission path defines an acoustic discontinuity. By selectively disposing the workpiece in the transmission path, measurements using the ultrasonic waves being transmitted with and without the presence of the workpiece can be compared. Additional steps of the method include transmitting the waves through the transmission path, receiving signals corresponding to the transmitted and reflected waves, recording time and amplitude data for each of the received signals, calculating a speed of sound in the workpiece based on the data, and calculating a thickness of each wall of the workpiece based on the data and the calculated speed of sound.

Optionally, the method can include additional steps, such as compensating the speed of sound and the thickness calculations due to temperature variations in the acoustic couplant medium. The steps of the present method obviate having to rely on a predetermined value for the speed of sound. The received signals can be used in either a time-domain or frequency-domain analysis, utilizing equations specific to the respective domains to determine speed of sound (time-domain), phase and group velocities (frequency-domain) and wall thickness quantities. Preferably, the workpiece is disposed in the transmission path such that during the step of transmitting the waves, they impinge substantially orthogonal to the outer and inner surfaces of the workpiece, helping to minimize distortion errors.

According to another aspect of the invention, a system for determining the wall thickness of an object and the speed of sound within the object from a single set of recorded ultrasound data is disclosed. The system comprises an acoustic couplant medium configured to selectively receive a tubular workpiece therein such that the workpiece, when present, is disposed within a transmission path defined in the medium. Each interface between a surface of the workpiece and the medium defines an acoustic discontinuity. The system further includes at least one ultrasonic wave transducer configured to transmit and receive signals corresponding to time and amplitude data from transmitted and reflected

waves, as well as signal receiving and recording apparatus operatively coupled to the transducers. The signal receiving and recording apparatus is configured to calculate the speed of sound within the workpiece based on the received signals without having to determine the temperature of the workpiece. From there, it can use the recorded ultrasound data and the calculated speed of sound to calculate the thickness of each wall of the workpiece. Optionally, the signal processing apparatus is configured to effect either a time-domain or frequency-domain analysis.

According to yet another aspect of the invention, a method of determining the wall thickness of and speed of sound within a tubular workpiece is disclosed. Steps used in the method include configuring an acoustic couplant medium, placing at least one ultrasonic transducer in acoustic communication with the medium, transmitting and receiving an ultrasonic wave through the medium without the tubular workpiece present in the medium, and recording data corresponding to the transmitted wave. Other steps include placing the workpiece in the medium, generating ultrasonic waves within the medium such that at least a portion of the waves are reflected back from at least one surface of the tubular workpiece and at least a portion of the waves are transmitted through the medium and the workpiece, detecting signals correspond to a portion of the waves reflected off the at least one surface of the tubular workpiece and a portion of the waves transmitted through the couplant medium and the tubular workpiece, recording data for each of the detected signals, calculating a speed of sound in the workpiece based on the data, and calculating a thickness of the walls of the workpiece based on the data and the calculated speed of sound. Optionally, the method can include the additional steps of extracting the spectral content of each of the detected signals from the time of flight data, and generating output signals for a plurality of discrete frequencies within the spectral content, where the output signals are proportional to the wall thickness of at least one wall of the tubular workpiece.

According to still another aspect of the invention, a method of determining the wall thickness of and speed of sound within a hollow workpiece is disclosed. The method comprising the steps of configuring an acoustic couplant medium and defining a transmission path therein, selectively disposing the hollow workpiece in the medium such

that the workpiece is in the transmission path, defining an acoustic discontinuity at each interface between a surface of the workpiece and the medium along the transmission path, transmitting a plurality of ultrasonic waves through the transmission path such that at least one of the waves being transmitted is without the presence of the workpiece in the transmission path, receiving signals corresponding to the waves reflected from at least one acoustic discontinuity and the waves that traverse the substantial entirety of the transmission path, measuring time of flight data for each of the received signals, calculating a speed of sound in the workpiece based on the recorded data, and calculating a thickness of each wall of the workpiece based on the measured time of flight data and the calculated speed of sound. Optionally, the method comprises the additional steps of extracting the spectral content of each of the received signals, and generating output signals for a plurality of discrete frequencies within the spectral content, where the output signals are proportional to the thickness of the walls of the workpiece.

According to another aspect of the present invention, a method of determining the wall thickness of a tubular workpiece and the speed of sound within the tubular workpiece is disclosed. The steps of the method include configuring an acoustic couplant medium, placing at least one ultrasound transducer within the couplant medium, defining a transmission path in the acoustic couplant medium, transmitting a first ultrasound pulse through the medium when the tubular workpiece is disposed therein such that at least a portion of the first pulse echoes off at least one surface of the workpiece, transmitting a second ultrasonic pulse through the medium when the workpiece is disposed therein such that at least a portion of the second pulse echoes off at least one surface of the workpiece, transmitting a third ultrasonic pulse through the medium when the tubular workpiece is disposed therein such that at least a portion of the third pulse passes diametrically through the substantial entirety of both the workpiece and the medium, transmitting a fourth ultrasonic pulse through the medium when the workpiece is not disposed therein such that at least a portion of the fourth pulse passes diametrically through the substantial entirety of the medium, detecting signals corresponding to the transmitted first through fourth pulses, recording time and amplitude data for the detected signals, calculating a speed of sound in the workpiece based on the data, and calculating a thickness of each wall of the workpiece

based on the data and the calculated speed of sound. Optionally, the method includes the step of wherein the first ultrasonic pulse is generated by a first transmitting device, and the second ultrasonic pulse is generated by a second transmitting device.

According to yet another aspect of the present invention, a method of determining the wall thickness of a tube and speed of sound within the tube is disclosed. The method includes the steps of selectively disposing the tube in an acoustic couplant medium, placing at least one ultrasonic transducer within the couplant medium, defining a transmission path in the medium, defining an acoustic discontinuity along the transmission path at each interface between a surface of the tube and the medium, generating a plurality of ultrasound waves at least one of which is done so without the presence of the tube in the transmission path, recording data corresponding to the portion of the waves that reflects off the first of the acoustic discontinuities encountered along the transmission path, recording data corresponding to the portion of the waves that reflects off the second of the acoustic discontinuities encountered along the transmission path, recording data corresponding to the portion of the waves that reflects off the third of the acoustic discontinuities encountered along the transmission path, recording data corresponding to the portion of the waves that reflects off the fourth of the acoustic discontinuities encountered along the transmission path, recording data corresponding to the portion of the waves that passes through the tubular member and across the substantial entirety of the transmission path, recording data corresponding to the portion of the waves that passes across the substantial entirety of the transmission path when the tubular member is not disposed therein, calculating a speed of sound in the tube based on the recorded data, and calculating a thickness of each wall of the tube based on the calculated speed of sound and the recorded data.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The following detailed description of the preferred embodiments of the present invention can be best understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:

FIG. 1A shows the echo signal paths between each transducer and a tubular workpiece according to an embodiment of the present invention;

FIG. 1B shows the transmission signal path between transducers when the tubular workpiece is present in the signal path;

FIG. 1C shows the transmission signal path between transducers when the tubular workpiece is removed from the signal path;

FIG. 2 shows a perspective view of the embodiment depicted in FIGS. 1(a)-(c) mounted into a measurement chamber;

FIG. 3 shows the waveforms of recorded pulses, including pulses reflected back from the outer and inner surfaces of the polyethylene tube, as well as the transmitted pulses with and without the tube inserted between the two transducers, respectively;

FIG. 4 shows a plot of dispersion for data taken from measurements on a polyethylene tube;

FIG. 5 shows a block diagram representative of the system of the present invention for measuring the wall thickness of a tubular object; and

FIGS. 6A through 6D show an alternate embodiment of the present invention, where the echo signal paths are between a single transducer, tubular workpiece and reflector.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring first to FIGS. 1A through 1C, 2 and 5, a set-up for the use of ultrasonic measurement of a tube is shown. In the present context, the term "measurement" and its variants is understood to include ways of sensing or otherwise detecting a particular

quantity, such as time or amplitude of ultrasound signals. In such a context, a measurement is a subset of the larger "determining", wherein quantities are not only measured, but processed or manipulated (such as by calculation or related computation) to produce a human- or machine-useable output. For example, measured time of flight data may be used to calculate, and thereby determine, speed of sound and thickness values. Referring with particularity to FIG. 2, the set-up includes an object to be measured **10** (in this case, a tube), a measurement chamber **15** (such as a vat), an acoustic couplant medium **20** (typically distilled water), measurement and control electronics **30**, a temperature sensor **40**, an object positioning device **50**, and a pair of transducers **T1** and **T2**. The transducers are capable of both sending and receiving ultrasonic signals, and the path between them makes up transmission path **60**. In addition, phase and echo waveform distortion due to the curvature in the tube walls can be minimized through the use of focused transducers such that the closest point on the surface of the tube being measured is placed at the transducer's focal distance. Preferably, these focused transducers are used so that the ultrasound beam width at the measurement site is three to five times smaller than the inner diameter of the tube. The control electronics **30** has numerous components, preferably including a pulser/receiver set **32**, made up of a pulser **32A** and receiver **32B**, digitizer **34**, controller and processor **35** and output **36** (typically in the form of a display, printout or data recorded to a mass storage device). A multiplexer **31** is used to switch the signals exchanged between the control electronics **30** and the transducers **T1** and **T2**. An alternative embodiment (not shown) could use a pair of pulser/receiver sets, each dedicated to a respective transducer, thereby eliminating the need for the multiplexer **31**. Alternatively, instead of using a digitizer, an analog processor (such as a comparitor and a counter, neither of which are shown) can be used to measure the time delay of received ultrasound pulses.

FIGS. 1A through 1C show the signal paths coming from and returning to the transducers for the dispersion measurement. In FIG. 1A, $P_0(t)$ is the initial pulse launched by the transducer **T1**. The echoes reflected back from the outer and inner surfaces of the first wall of the tube **10** (with a thickness L_1) are recorded as $R_1(t)$. Similarly, transducer **T2** sends a pulse and the echoes reflected back from the two surfaces of the second wall on the opposite side (with a thickness L_2) are recorded as $R_2(t)$. Next, transducer **T1** sends a

pulse which passes through both walls of tube **10** and is recorded by transducer **T2** as $T_t(t)$, as shown by FIG. 1B. Finally, as shown in FIG. 1C, the tube **10** is removed and a pulse which passes through the transmission path **60** is recorded as $T_w(t)$. It will be appreciated by those skilled in the art that the precise order of the foregoing measurements is not critical, and that the above-recited order is meant to be representative of all such sequences. By virtue of the ultrasound data acquired by the present method, one-sided transducer access to each wall of the tube is possible. This is important in applications requiring wall thickness measurement in physically small spaces, into which conventional transducers and microphones are unable to fit.

Based on the four sets of measurements $R_1(t)$, $R_2(t)$, $T_t(t)$ and $T_w(t)$, the sound speed within and wall thickness of the tube **10** can be determined using the time-domain analysis. Referring now to FIG. 3, if Δt_1, Δt_2 and Δt_3 denote the time delay between the two echoes associated with L_1, the time delay between the two echoes associated with L_2, and the time delay between $T_w(t)$ and $T_t(t)$, respectively, the following set of equations can be derived:

$$\Delta t_1 = \frac{2L_1}{c} \qquad (1)$$

$$\Delta t_2 = \frac{2L_2}{c} \qquad (2)$$

$$\Delta t_3 = \frac{L_1 + L_2}{c_w(T)} - \frac{L_1 + L_2}{c} \qquad (3)$$

where $c_w(T)$ is the temperature-dependent speed of sound in water. From the above three equations, c can first be solved:

$$c = c_w(T)\left[\frac{2\Delta t_3}{\Delta t_1 + \Delta t_2} + 1\right] \qquad (4)$$

From equation (4), it can be seen that the value of c, the speed of sound in the object being measured, is only dependent on the speed of sound in the water (which can be easily determined from the measured temperature) and the three time delays Δt_1, Δt_2 and Δt_3 associated with the various times of flight. This is significant, as errors associated with temperature differences between the water and the object being measured are reduced, since

any temperature dependencies of the speed of sound fall out of the time of flight data and subsequent calculations. Using the value of c obtained by equation (4), the thickness of the two walls L_1 and L_2 can then be solved as:

$$L_1 = \frac{c\Delta t_1}{2} \qquad (5)$$

$$L_2 = \frac{c\Delta t_2}{2} \qquad (6)$$

It will be appreciated by those skilled in the art that it is not necessary to calculate the quantity "c" first, merely that such an approach is one way to perform the calculations. For example, by substituting the quantity on the right hand side of equation (4) into equations (5) and (6), the thickness of the two walls L_1 and L_2 can be directly calculated from Δt_1, Δt_2, Δt_3 and c_w without first calculating "c". In situations where the tube material is substantially dispersive, additional accuracy in the determination of c, L_1 and L_2 can be obtained using the frequency domain analysis. By using $A(f)e^{-j\theta(f)}$ to represent the Fourier transform of an ultrasonic pulse, the following set of equations can be derived:

$$\frac{1}{V_p(f)} = \frac{\Delta\theta_1(f)}{4\pi f L_1} \qquad (7)$$

$$\frac{1}{V_p(f)} = \frac{\Delta\theta_2(f)}{4\pi f L_2} \qquad (8)$$

$$\frac{1}{V_p(f)} = \frac{1}{c_w(T)} - \frac{\Delta\theta_3(f)}{2\pi f (L_1 + L_2)} \qquad (9)$$

where $\Delta\theta_1$(f) and $\Delta\theta_2$(f) are, respectively, the differences between the phase spectra of the two echoes associated with L_1 and the two echoes associated with L_2, after the extra 180^0 phase shift of the second echo is removed, and $\Delta\theta_3$(f) is the difference between the phase spectra of the two transmitted pulses T_w(t) and T_t(t). It will be appreciated by those skilled in the art that equations (7) through (9) are the frequency-domain analogues to time-domain equations (1) through (3). In the preceding derivation, it was assumed that for all practical purposes the dispersion of water is negligible. From these three equations, V_p(f), L_1 and L_2 can be solved:

$$V_p(f) = c_w(T)\left[\frac{2\Delta\theta_3(f)}{\Delta\theta_1(f)+\Delta\theta_2(f)}+1\right] \qquad (10)$$

$$L_1 = \frac{\Delta\theta_1}{4\pi f}V_p(f) \qquad (11)$$

$$L_2 = \frac{\Delta\theta_2}{4\pi f}V_p(f) \qquad (12)$$

Equation (10) for $V_p(f)$ gives the phase velocity as a function of frequency. As with equation (4) of the time-domain analysis, it highlights that the present method does not require direct measurement of the temperature of the tube walls. From $V_p(f)$, the group velocity, $V_g(f)$, can be calculated:

$$V_g(f) = \frac{V_p(f)}{1-\dfrac{f}{V_p(f)}\dfrac{dV_p(f)}{df}} \qquad (13)$$

If the tube material is not dispersive (such that V_p is a constant), then the phase velocity V_p, group velocity V_g, and the speed of sound c, defined in the previous time-domain analysis, are all the same. On the other hand, if the dispersion is not negligible, V_g can be significantly different from V_p, and c takes a value of V_g at some frequency near the center frequency of the transducer **T1**.

The following experimental example will be used to explain the attributes of the present invention. In the experiment, a polyethylene tube sample is used which has a nominal outer diameter of 9.53 mm (3/8 inches) and a nominal inner diameter of 6.35 mm (1/4 inches). Both time-domain analysis and frequency-domain analysis are performed. Additional experimental results for four tube samples made from different materials can be found in an article entitled Simultaneous Measurement of Sound Velocity and Wall Thickness of a Tube, Ultrasonics 39 (2001) 407-411, by the present inventor, and hereby incorporated by reference.

The experimental setup is shown conceptually in FIGS. 1A-C, 2, and 5. A pair of identical transducers (Panametrics V309, 5.0 MHz, 13-mm aperture, point focus, 25.4-mm focal distance) are used as **T1** and **T2**. The outer surface of the tube **10** is placed near the focal distance of the transducers. Switching can be accomplished either manually or through a conventional multiplexer **31**, while the pulser/receiver set **32** is a Panametrics 5052PR. The amplified pulse is digitized by a SONY/TEK 390AD programmable digitizer **34**, which includes an adjustable digital delay for triggering the sampling window. Each sampling window contains 256 samples, and has a sampling frequency of 60 MHz. The signals are averaged 30 times and then transferred to the controller and processor **35** (such as that found in a conventional personal computer) and processed using a standard mathematics software package, such as MATLAB, distributed by MathWorks, Natick, MA. Output **36** can be in the form of printouts, visual display or data sent to a mass storage device (such as a hard disk drive). The water temperature was measured by probe **40**, and found to be 21°C, which corresponds to a c_w of 1485 m/s.

Referring again to FIG. 3, the waveforms of the two reflected signals $R_1(t)$, $R_2(t)$ and the two transmitted signals $T_s(t)$, $T_w(t)$ are shown. For the time-domain analysis, the time delays Δt_1 and Δt_2 are measured from the zero-crossing right before the largest positive peak of the first echo to the zero-crossing right before the largest negative peak of the second echo to take account for the extra 180^0 phase shift between the two echoes. The time delay Δt_3 is measured from the zero-crossing right before the largest positive peak of T_s to the zero-crossing right before the largest positive peak of T_w. From the measured time delays, c, L_1 and L_2 are calculated using equations (4), (5) and (6). The results are summarized on the left side of Table 1.

Time-domain Analysis	Frequency-domain Analysis
$\Delta t_1 = 1.418$ (μs) $\Delta t_2 = 1.415$ (μs) $\Delta t_3 = 0.597$ (μs) $c = 2.11\times10^3$ (m/s)	$V_p = 2067 + 2.156\,f$ (m/s) [f = 2 ~ 8 MHz] $V_g = 2089$ (m/s) [f = 5 MHz]
$L_1 = 1.50$ (mm)	$L_1 = 1.483 \pm 0.005$ (mm) [f = 3 ~ 7 MHz]
$L_2 = 1.49$ (mm)	$L_2 = 1.484 \pm 0.004$ (mm) [f = 3 ~ 7 MHz]

Table 1: Results from the polyethylene tube using the time-domain analysis and frequency-domain analysis.

To perform the frequency-domain analysis, the two echoes contained in $R_1(t)$ are first separated while keeping their temporal relation. The phase difference $\Delta\theta_1$ between the two echoes is then determined using a procedure described in an article entitled Measurement of Acoustic Dispersion Using Both Transmitted and Reflected Pulses, J. Acoust. Soc. Am. 107 (2000) 801-807, (hereinafter Measurement Article) by the present inventor, and hereby incorporated by reference. The phase difference $\Delta\theta_2$ between the two echoes contained in $R_2(t)$, as well as the phase difference $\Delta\theta_3$ between $T_w(t)$ and $T_s(t)$, is also determined in a similar way. The phase velocity $V_p(f)$ is then calculated using equation (10). Referring now to FIG. 4, the solid line represents $V_p(f)$, calculated from data taken and manipulated according to equation (10), in the frequency range between 2 and 8 MHz. A linear regression (dashed) line having a slope of 2.156 m/s per MHz is also shown. Using this value of the slope and a phase velocity of 2078 m/s at 5MHz, the group velocity at 5 MHz is calculated using equation (13) as 2089 m/s. This value is 1% smaller than 2110 m/s value determined using the time-domain analysis. When equations (11) and (12) are used to calculate the wall thickness, the values of L_1 and L_2 are actually functions of frequency; however, the changes of L_1 and L_2 within the useful frequency range of the measurement system, which are due to noise, should be very small. The means and standard deviations of L_1 and L_2 in the frequency range of 3 to 7 MHz are listed in Table 1. As with the velocity calculations, the difference between the thickness determined by the time-domain analysis and the frequency-domain analysis is about 1%. The general trend shown in FIG. 4, that of the phase velocity V_p increasing with increasing frequency, is typical of most materials, and is consistent with predictions. The close agreement between the time-domain value for the speed of sound and the frequency-domain value for the phase velocity also indicates that the present method is internally consistent, and that the polyethylene used in the tube does not exhibit marked dispersive properties.

When the curve of V_p in FIG. 4 for the tube is compared with the smooth curves for measurements made on flat plates, as shown in figures 5 through 7 of the aforementioned Measurement Article, it is apparent that the phase velocity obtained from the tube sample is

significantly noisier. This is to be expected, as phase distortion is produced by the curved tube walls, since portions of the wave pass through longer, refracted paths than others. The pulse returns emanating from the curved wall surface make precise determination of the onset of pulse detection more difficult, as there is a less clear line of demarcation between discrete pulses. This distortion is decreased when the ratio of the beam width to the diameter of the tube decreases. To minimize phase distortion, focused transducers should be used and the front surface of the tube should be placed at the focal distance of the transducer. In the experiment with the polyethylene tube, the –6dB beam width is about 0.6 mm, which is ten times smaller than the inner diameter of the tube. A general guideline is that the beam width at the measurement site should be at least between three and five times smaller than the inner diameter of the tube. Even with the rippling effect caused by distortion, the size of the individual excursions are small (on the order of 3 m/s or less) relative to the phase velocity spread (between 10 and 15 m/s) over the frequency band between 2 and 8 MHz. It will be appreciated by those skilled in the art that the noise shown in FIG. 4 is not unique to the present invention; conventional measurements taken in the time-domain on tubular objects also capture the noise, it is just that such noise does not show up on a plot such as FIG. 4. The conventional approach can be fraught with measurement inaccuracy for the very reason that because the noise does not manifest itself in the plotted or tabulated results, it is assumed to not exist. By contrast, the measurement approach of the present invention allows the user to determine if modifications to the hardware setup or calculation routine is necessary to ensure optimum accuracy.

Alternate component configurations can be employed. Referring next to FIGS. 6A through 6D, the current method can be implemented by using only one transducer **T1** and a reflector **70**. In such a variation, as shown in FIG. 6A, transducer **T1** is first used to send out pulse $P_0(t)$ that gets reflected off reflector **70** and returned to transducer **T1** as reflected echo $R_1(t)$. This step is repeated with the tube **10** in place, as shown in FIG. 6B; the difference between the time of arrival of the pulses in the first two steps of FIGS. 6A and 6B equals $2\Delta t_3$, where Δt_3 is the difference of one-way pulse travel times in the two-transducer configuration shown in FIGS. 1A through 1C. In the next step, as shown in FIG. 6C, additional reflections from the tube **10** are recorded by transducer **T1** to acquire Δt_1. In

FIG. 6D, transducer **T1** can be moved such that it can replace transducer **T2** to produce a signal corresponding to reflected echo $R_2(t)$, thus allowing acquisition of Δt_2. By a process similar to that used above in conjunction equations (1) through (12), the speed "c" and wall thickness L_1 and L_2 of the tubular object can be calculated.

Having described the invention in detail and by reference to preferred embodiments thereof, it will be apparent that modifications and variations are possible without departing from the scope of the invention defined in the appended claims. More specifically, although some aspects of the present invention are identified herein as preferred or particularly advantageous, it is contemplated that the present invention is not necessarily limited to these preferred aspects of the invention.

What is claimed is: